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THESIS

ATOMIZATION OF
JP-10/B_4C
GELLED SLURRY FUEL

by

John David Guglielmi

June, 1992

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Atomization of $JP\text{-}10/B_4C$ Gelled Slurry Fuel

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

The atomization of a gelled boron slurry fuel using two commercially available airblast atomizers was studied at atmospheric pressure in non-reacting flow. The atomization of water was also characterized for comparison. Each atomizer was operated at two different liquid mass flow rates and several air/fuel ratios. Drop size distribution was measured using a Malvern 2600 HSD Laser Diffraction Particle Sizer. Drop sizes acceptable for use in ramjet combustors could be obtained for the gelled slurry fuel from both atomizers. However, this required air/fuel ratios too high for practical applications. It appears that secondary atomization methods or different types of atomizers will be required to obtain high ramjet combustion efficiencies with these fuels if they are to be used over typical ramjet operating envelopes.

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I. INTRODUCTION

In the design of tactical air-launched missiles, the designer is often constrained by the missile's volume more than any other parameter. The ever increasing demand for longer range missiles requires one of two things--either a more efficient propulsion system or a way to provide more energy to the existing system, while operating within the constrained volume. Current gas turbine engines operate at 95 to 100 percent combustion efficiency, but within a relatively small altitude/supersonic Mach number envelope. Further advances in gas turbine performance for supersonic tactical missiles will come at an ever increasing cost. Current supersonic tactical missile applications favor ramjet propulsion systems for their high efficiency over a much larger altitude/supersonic Mach number operating envelope as well as for the high fuel system turn down ratios.

Slurry and gelled slurry fuels are being studied for their high volumetric energy content. Slurry fuels can have nearly twice as much energy per unit volume as liquid fuels, which makes them much more attractive for volume-limited tactical missile applications. Boron, beryllium, carbon, aluminum, and silicon are the elements with the five highest volumetric heat capacities. Boron, with 483,800 btu/gal, has the potential to significantly increase ramjet performance. The high solid

content of these fuels, however, causes them to separate during prolonged storage. To prevent separation, and thereby stabilize this mixture, a gelling agent is added. While this may overcome the storage problem it creates another, in that the fuel is now more difficult to atomize.

Over the past several years NASA has been analyzing the atomization of gelled and metallized gelled propellants for their liquid rocket applications. These high density gelled liquid propellants have the potential for markedly increasing the payload of current and future launch vehicles and orbiters. [Ref.1]

Coal/water, coal/oil, carbon slurry, and other high viscosity fuels have been analyzed extensively since the 1970's. Previous work in this area has shown that mechanical atomizers do not effectively break up fuel slurries [Ref. 2]. For these high viscosity fuels to achieve the high degrees of atomization and combustion efficiency required for tactical missile applications, airblast atomization is thought to be generally required. When atomizing air is used at low flow rates with a low density, low viscosity liquids, drop size decreases rapidly. As air mass flow rate is increased, drop size eventually reaches a minimum. Further increases in air mass flow rate do not result in substantive drop size reduction. To achieve the maximum possible atomization (minimum drop size) of a low viscosity fuel at the lowest

possible pressure, the airblast atomizer typically must operate at air/fuel ratios of approximately 4 to 6 [Ref 3].

For a low viscosity fuel, Lefebvre showed that the Sauter-mean diameter (D_{32}) is related to the characteristic dimension of the fuel stream at the fuel/atomizing air interface by:

$$D_{32} \propto t^{3.75} \tag{1}$$

where t = film thickness at the fuel air interface [Ref. 3].

For a plain-jet airblast atomizer he also experimentally obtained the following expression for D_{32} in terms of the air/fuel properties and the dimensions of the atomizer orifice, for both water and kerosene:

$$\begin{gathered} D_{32} = 0.95\left[\frac{(\sigma_l W_l)^{0.33}}{V_r \rho_l^{0.37} \rho_a^{0.30}}\right]\left[\frac{1+W_l}{W_a}\right]^{1.70} \\ 0.13\mu_l\left[\frac{D}{\sigma_l \rho_l}\right]^{0.5}\left[1+\frac{W_l}{W_a}\right]^{1.70} \end{gathered} \tag{2}$$

where σ_l = surface tension of the liquid, N/m
ρ_l = density of the liquid, kg/m^3
ρ_a = density of air, kg/m^3
W_l = mass flow rate of liquid, g/s
W_a = mass flow rate of air, g/s
V_x = relative velocity (air minus liquid), m/s
D = diameter of fuel injection orifice, mm
μ_l = viscosity of the liquid, kg/ms. [Ref. 3]

To identify the range of properties for high density, high viscosity fuels that are best suited for use in volume limited

ramjets, a study of the effects of injector design on atomization quality is needed. Past studies have shown that the optimum atomization attainable for a particular fuel is a function of the conditions at which it is being atomized (air/fuel ratio, velocities, etc), as well as the properties of the fuel and location of the atomizer within the air inlet or combustor [Refs. 2 & 3]. Gany [Ref. 4] and Faeth [Ref. 5] have shown that in ramjet combustors, where the residence times are typically 5 ms, boron particles in the 5-10μm are required to obtain complete combustion of slurried fuels in gas turbine combustors. Acceptable drop sizes for complete combustion of liquid fuels in gas turbine engines are in the 30-40 μm range. Lipinski has suggested that primary atomization of a gelled slurry fuel to 40 μm would give acceptable combustion efficiencies as long as some secondary atomization mechanism were present to reduce the particles to approximately 10 μm [Ref. 6]. He proposed the use of a more volatile fuel additive, such as magnesium, that would tend to burst the liquid/solid fuel agglomerate when it is exposed to the high temperature of the combustor. His data indicated that Sauter mean diameters (D_{32}) in the 30-40 μm range could be obtained from a gelled slurry fuel (loaded with 60 percent solids) when using airblast atomizers with air/fuel ratios of 5:1. However, most test conditions with unheated fuels resulted in values of D_{32} larger than 70 μm.

It should be mentioned that very low atomizer air/fuel ratios (e.g. 0.05) would be required in ramjet applications since the air for atomization would have to be (turbo) pumped to higher pressures and combustor air/fuel ratios must often operate near stoichiometric conditions. It remains to be seen if adequate atomization can be obtained using the low air/fuel ratios.

The gelled slurry fuel study being conducted at the Naval Postgraduate School (NPS) is aimed at optimization of the atomization process and the combustion efficiency of a gelled JP-10/B_4C slurry fuel, currently under development at the Naval Air Warfare Center, Weapons Division, China Lake, California. It is hoped that non-reacting flow studies can result in the necessary data for maximizing combustion efficiency, without the increased cost associated with reacting flow experiments. The overall effort has three objectives. The first objective is addressed by the current investigation and is to determine the effects that injector design, operating pressure and air/fuel ratio have on D_{32} and the drop size distribution in a non-reacting environment. This should permit determination of the conditions necessary for obtaining acceptable drop sizes from each atomizer. To begin to understand the relationships between viscosity, density and atomizer design on the atomization obtainable from this fuel, two different atomizers were selected. The atomization quality achieved with this high viscosity, high

density slurry fuel was also compared to results obtained for a low viscosity, low density liquid (water), to earlier published data for low density liquids and to the data obtained by Lipinski. The second objective of the NPS effort is to determine the effect that injector location within the air ducting and/or combustor has on air/fuel mixing and penetration, drop size and distribution and residence time. This study will also be conducted in non-reacting flow using two-dimensional flow visualization. The third objective is to determine if the optimum atomization (objective 1) and optimum location (objective 2) determined using non-reacting flow measurements can be correlated with optimum combustion efficiencies obtainable in reacting flow experiments.

In this investigation, each atomizer was observed exhausting into ambient pressure using water and the gelled JP-10/B_4C fuel. To characterize the effect that chamber pressure may have on atomization quality, a windowed chamber with a translating nozzle was designed and fabricated. A Malvern 2600 HSD particle sizer was used to measure the drop size distribution at varying axial and radial distances from the injector tip.

II. EXPERIMENTAL APPARATUS AND TEST PROCEDURES

A. TEST APPARATUS

The experimental apparatus used for the characterization of the two commercially available atomizers consisted of a Malvern 2600 HSD Laser Diffraction Particle Sizer, a fuel delivery system and a windowed chamber with a translating injector head. This arrangement is shown in Figures 2.1 and 2.2. The chamber was designed to allow translation of the two different atomizers along its centerline. The windows were placed to provide maximum visibility of the fuel spray by the Malvern instrument. Nitrogen was distributed evenly around the circumference of each window through a sintered bronze filter in an attempt to avoid fouling of the windows by the injected spray. To prevent distortion of the spray pattern caused by the swirling of the combustion air, no air entered the chamber external to the atomizer and chamber pressure could be controlled by placing a choked converging nozzle at the exit of the chamber. The liquid mass flow rates were controlled by cavitating venturis which were individually calibrated for each fluid prior to testing. The air mass flow rates were controlled by placing sonicly choked nozzles in the air supply line. Operation was initiated with the atomizer located downstream of the windows, and as the atomizer was

moved forward in increments, drop size measurements could be made.

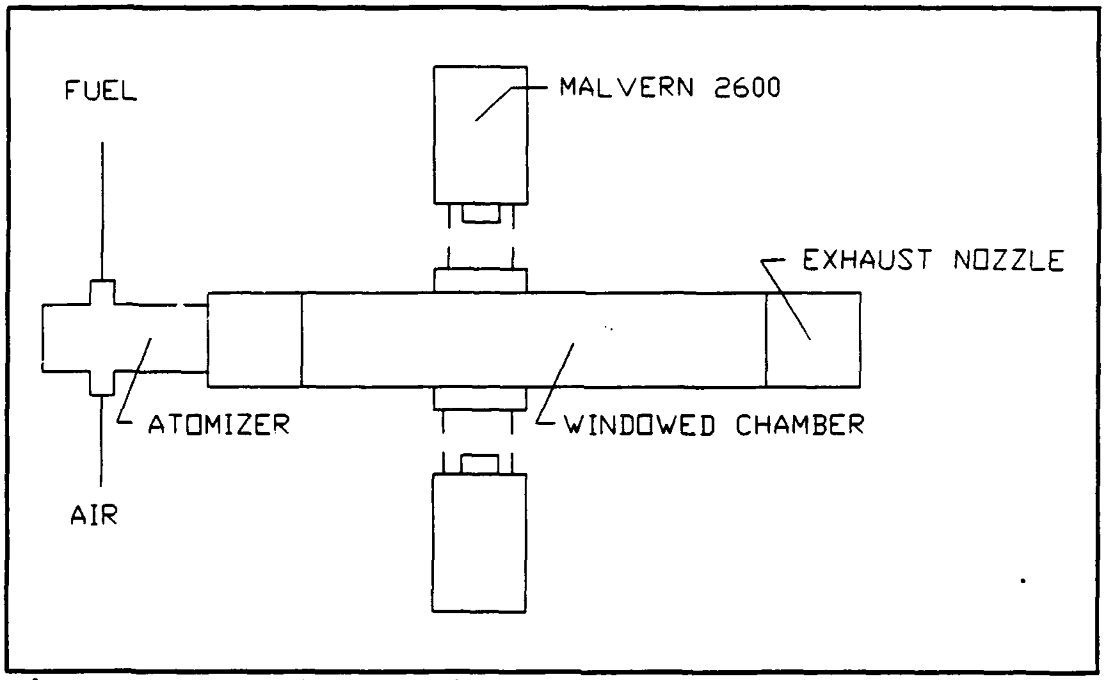

Figure 2.1: Test Apparatus

The first series of measurements were taken while spraying water and the JP-10/B_4C gel from the two atomizers across the analyzer beam in the open atmosphere. The drop size and distribution from each atomizer were measured at regular intervals along the spray centerline using the Malvern 2600 HSD. To examine the drop size and distribution at the edge of the injected spray, measurements were also taken at axial points 1.0 inch off centerline with the Monarch atomizer and 0.75 inch off centerline with the Delavan atomizer. This data was used to help determine under what conditions each atomizer was to be operated in the windowed chamber.

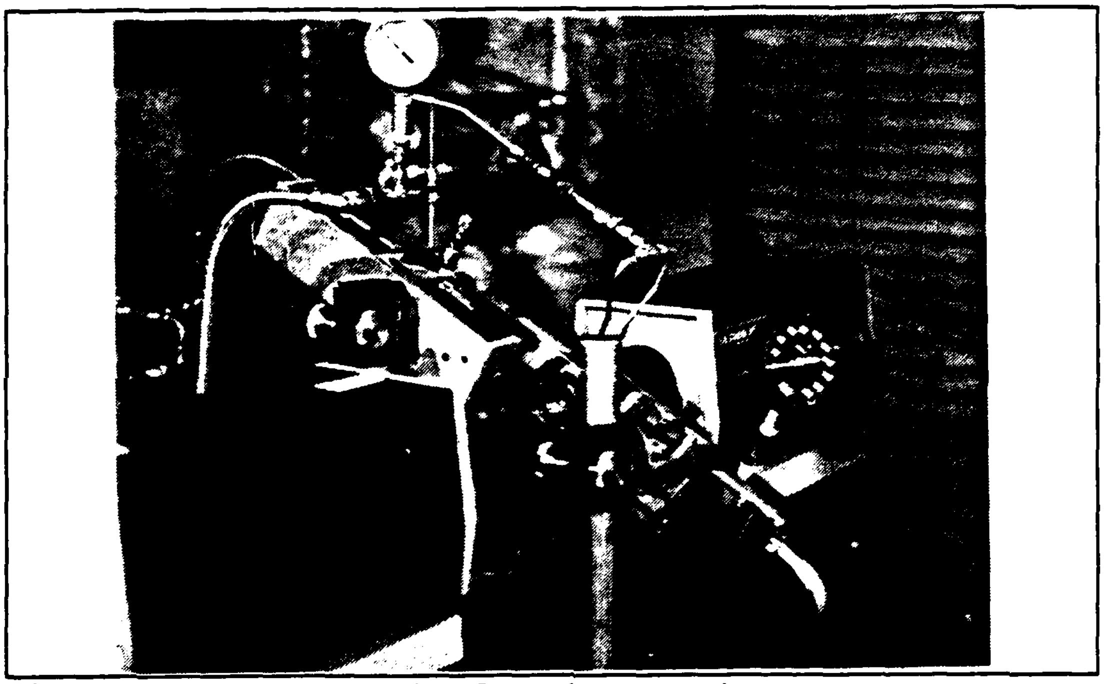

Figure 2.2: Photograph of Test Apparatus

The next series of tests was to be conducted with the two atomizers inserted in the windowed chamber to determine the effect that chamber pressure may have on the mean drop size and distribution.

1. Atomizers

The two atomizers tested were (1) a Monarch Manufacturing Works, Inc. air operated industrial oil burning nozzle, Model C-170-WA, with a nominal flow rate of 0.28 GPM and a nominal spray angle of 80 degrees, and (2) a Delavan, Inc. swirl-air nozzle, Model 32740 [Ref. 7], with a nominal flow rate of 1 GPM, and a nominal spray angle of 50 degrees. Both atomizers were slightly modified in external dimensions for use in the test apparatus and both are shown in Figure 2.3.

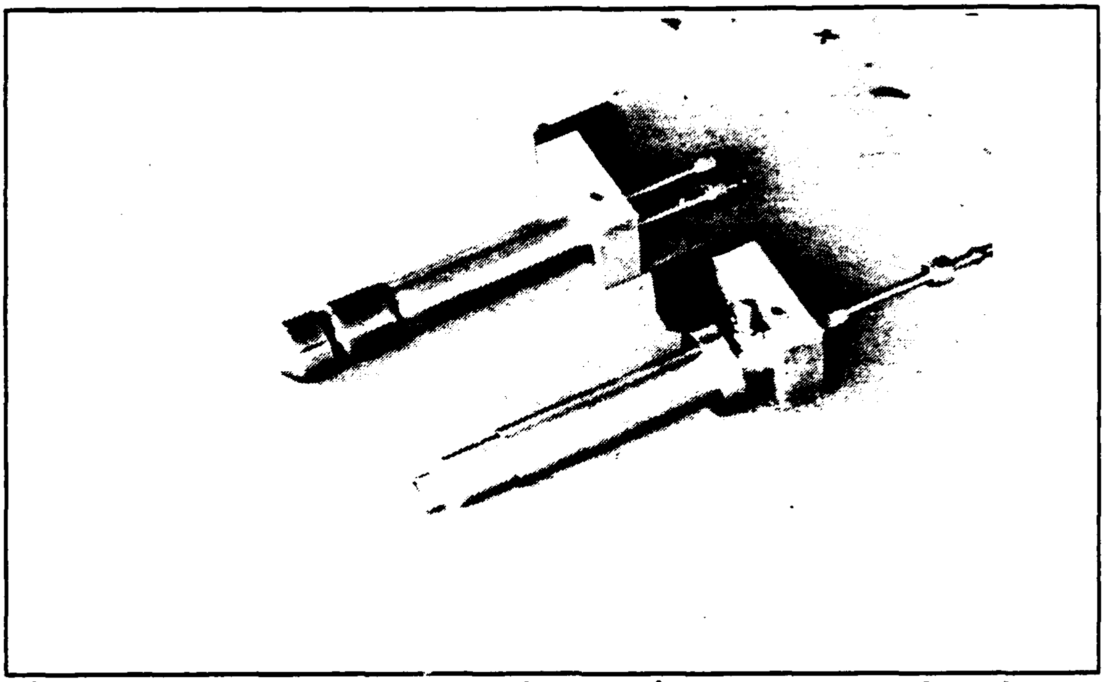

Figure 2.3: Photograph of Atomizers; Monarch Above, Delavan Below

2. Fuel System

The fuel system is shown in Figure 2.4 and 2.5. Two fuel tanks were used to provide positive expulsion of the slurry through the atomizers. The first tank was pressurized with nitrogen through a hand operated, dome loaded, regulator. Only the first tank was needed while testing with water because water was readily expelled under nitrogen pressure alone. The pressure versus mass flow rate behavior for water is shown in Figure 2.6 for both a 0.018 inch and a 0.020 inch throat diameter cavitating venturi.

To prevent mixing of the nitrogen gas or JP-10 with the gelled slurry, JP-10 was put in the first tank, and the JP-10/B_4C slurry was put in the second tank along with a piston.

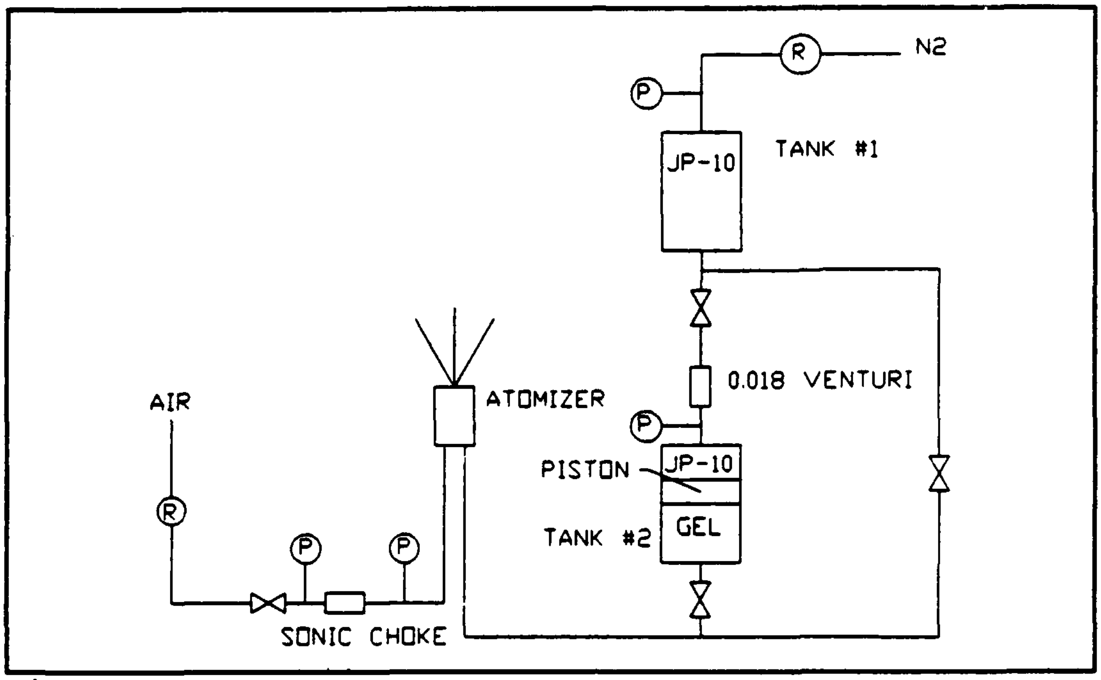

Figure 2.4: Fuel System

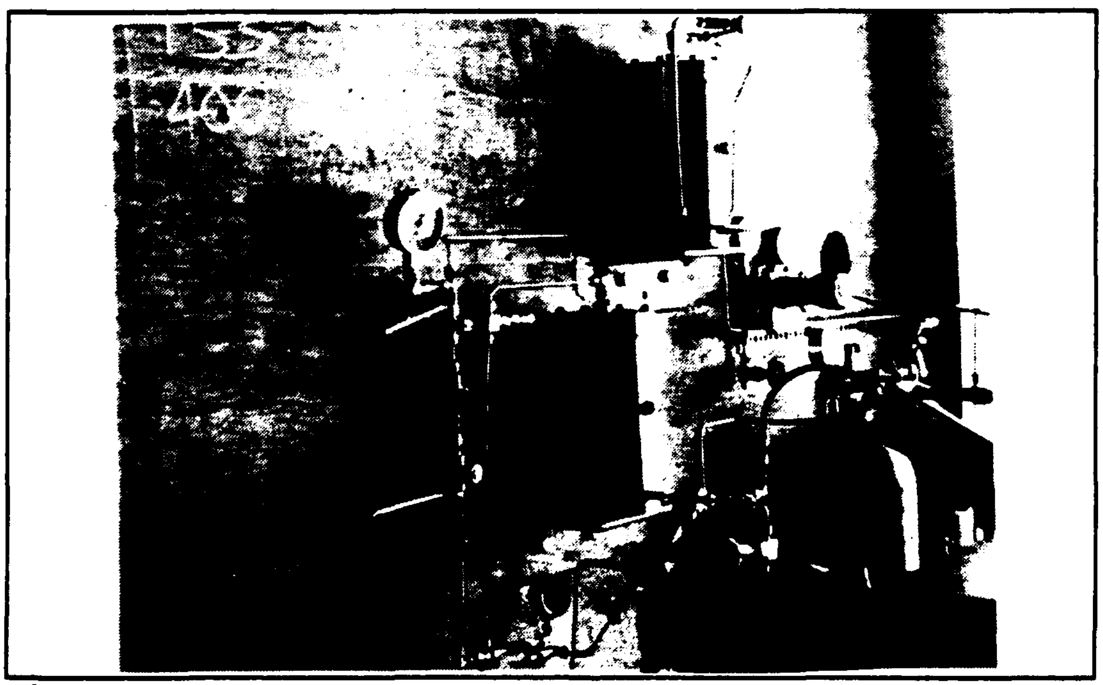

Figure 2.5: Photograph of Fuel System

Pressurized JP-10 flowed from the first tank through a 0.020 inch throat diameter, calibrated cavitating venturi and into the second tank. Since the JP-10 volume flow rate was equal to the slurry volume flow rate, the mass flow rate of the slurry could be accurately determined. Figure 2.7 is the calibration curve for the 0.020" throat diameter venturi.

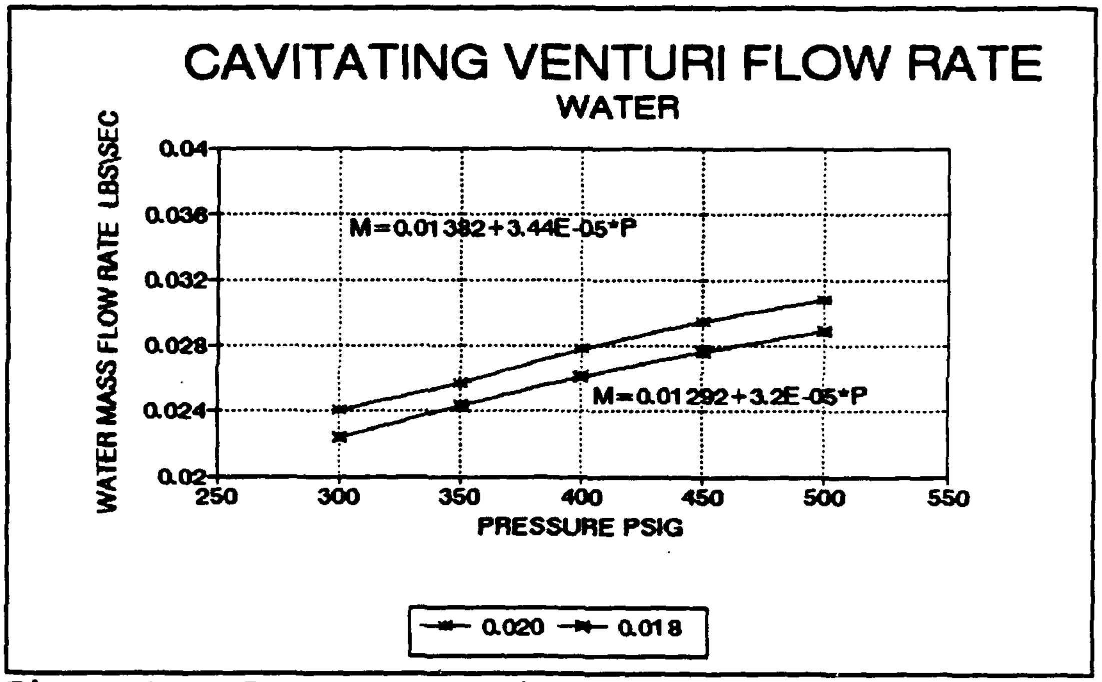

Figure 2.6: Pressure vs Water Mass Flow Rate for 0.018" and 0.020" Throat Diameter Cavitating Venturis

3. JP-10/B_4C Gelled Slurry Fuel

The gelled slurry fuel was provided by the Naval Air Warfare Center, Weapons Division, China Lake, California. It consisted of 50% solid boron carbide, 38% JP-10, a small amount of magnesium, a catalyst and a gelling agent. The D_{32}

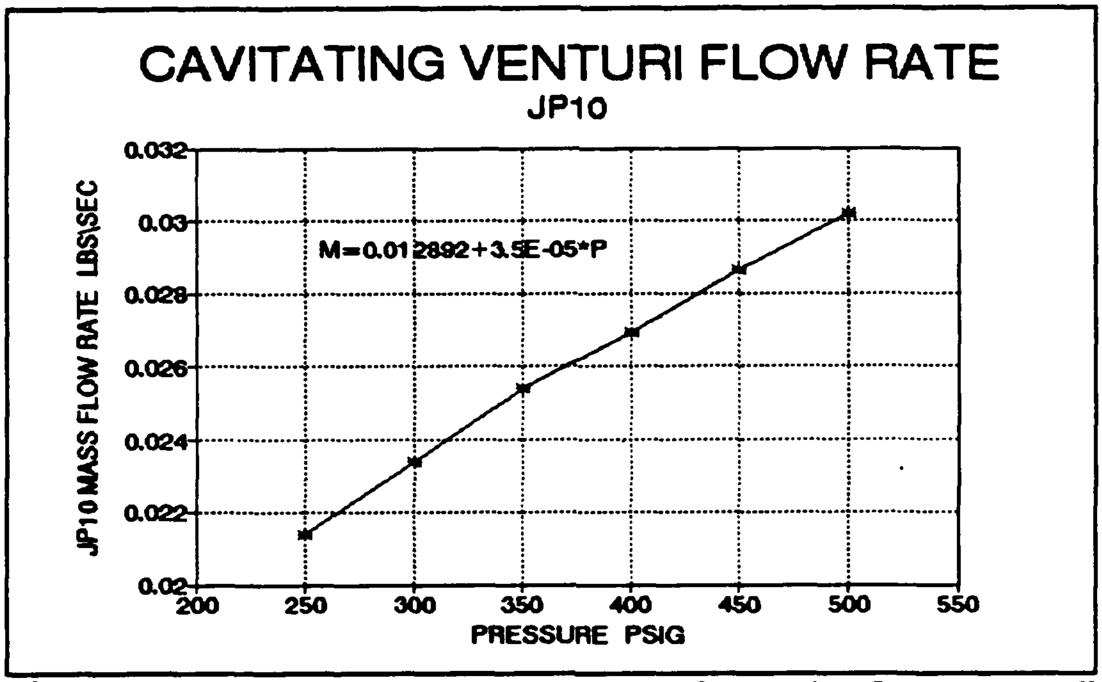

Figure 2.7: Pressure vs JP-10 Mass Flow Rate for a 0.020" Throat Diameter Cavitating Venturi

of the boron carbide particles was 9 µm, with most of the particles approximately 4 µm in diameter. The fuel was pitch black in color and had the consistency of cold molasses.

The gelled slurry was delivered in March, 1992, and was not tested until June, 1992. When the storage container was first opened, there was a thin film of clear, viscous liquid on top, that appeared to be JP-10 possibly mixed with some of the gelling agent and/or catalyst. As the gel was being loaded into the fuel tank, it appeared to have viscosity and density gradients across the radius of the storage container; the gel in the center of the container appeared slightly more dense and viscous than that at the outside edge.

B. MEASUREMENT TECHNIQUE

The Malvern 2600 HSD Laser Diffraction Particle Sizer was used to determine the mean particle size and distribution produced by both atomizers. It operates on the principle of ensemble light scattering and uses a 5 mW HeNe laser to generate a 9 mm diameter, collimated, monochromatic, analyzer beam. Fuel drops in the beam scatter this light, and it is collected by a range lens and focused on a diode array. The smaller the drop size, the larger the angle that the light ray will be scattered. Three different lens' are provided; 300 mm, 100 mm and 63 mm. Each lens has a vignetting distance, beyond which it will not collect light scattered at the larger angles. There are 31 annular rings on the diode array that detect light scattered at 31 different angles. Regardless of the drops' location or movement relative to the beam center, the Fourier transform property of the range lens produces a stationary diffraction pattern on the array. This information is then averaged for each ring and drop sizes are calculated. By taking drop size measurements at regular intervals from the atomizer tip, an accurate characterization of the distribution of drops with respect to their axial and radial position in the injected spray could be made.

III. PRESENTATION OF RESULTS

Each atomizer was tested at atmospheric conditions with water and the JP-10/B_4C gelled slurry fuel at two liquid mass flow rates, various air/fuel ratios and at several points throughout the injected spray. Data recorded from points near the atomizer tip, however, had values of obscuration approaching unity (and values of D_{32} significantly less than the manufacturer's data) [Ref. 7]. The effect of dense sprays on the Malvern 2600 HSD measurement is to give low values of D_{32}. This occurs because multi-scattered rays from the analyzer beam strike the diode array at greater angles than would result from a less dense spray. The high obscuration of the analyzer beam was caused by the extreme drop density of the injected spray in the near-tip region. The smaller than predicted D_{32} may have been partly caused by operating the atomizer at off-design conditions and partly by multi-scattering of the analyzer beam.

Felton [Ref. 8] and Chin, et. al. [Ref. 9] studied the effects that dense sprays have on drop size measurements using Malvern particle sizers. Chin used multiple injectors to generate a dense spray of known drop size. He then derived a correction factor from the measured D_{32} and the known D_{32}. His data was applicable to values of D_{32} between 15 μm and 80 μm, and for Rosin-Rammler distribution parameters between 1.2 and

1.9 [Ref. 9]. An alternative technique was investigated by Gülder and is outlined in Ref. 10. Gülder's correction applies to values of obscuration between 0.50 and 0.98, and for values of D_{32} between 10 μm and 100 μm. The latter technique was chosen for its application at lower values of D_{32}. Several of the recorded data in this investigation, however, still fell outside of these ranges and his equations had to be extrapolated to give a "best approximation" for D_{32}. The extrapolated correction curve which was used is shown in Figure 3.1.

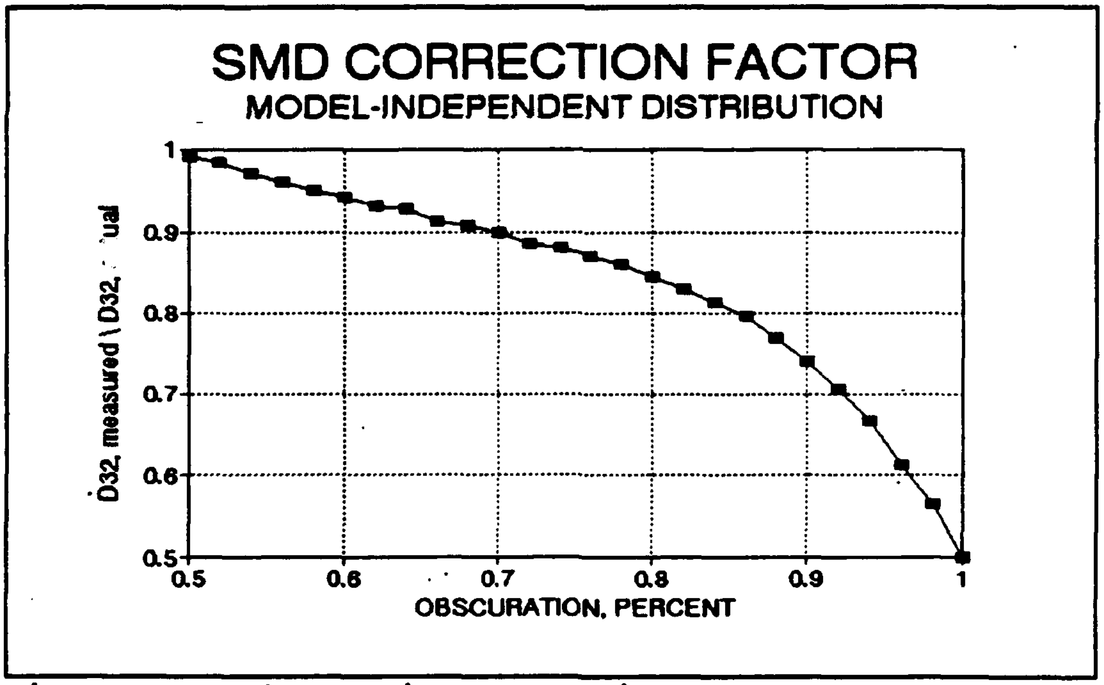

Figure 3.1: Obscuration Correction Factor Curve Adapted From Ref. 10

A. ATMOSPHERIC TESTS WITH WATER

The first series of tests were aimed at characterizing each atomizer with water. There is a large volume of data available from which a comparison can easily be made with these results. The data obtained were then analyzed to help determine at which operating conditions and where in the injected spray each atomizer should be evaluated when testing with the JP-10/B_4C gelled slurry fuel.

1. Delavan Atomizer

This atomizer was tested with water at mass flow rates of 0.02 lbs/s and 0.03 lbs/s, and air/fuel ratios of one-half, one, two and five. The spray angle was visually measured and found to be approximately 30 degrees. Drop size measurements were made with the 100 mm range lens which had a lower particle size measurement capability of 1.9 μm. The raw and corrected data for each of these sets of conditions are shown in Figures 3.2 to 3.9.

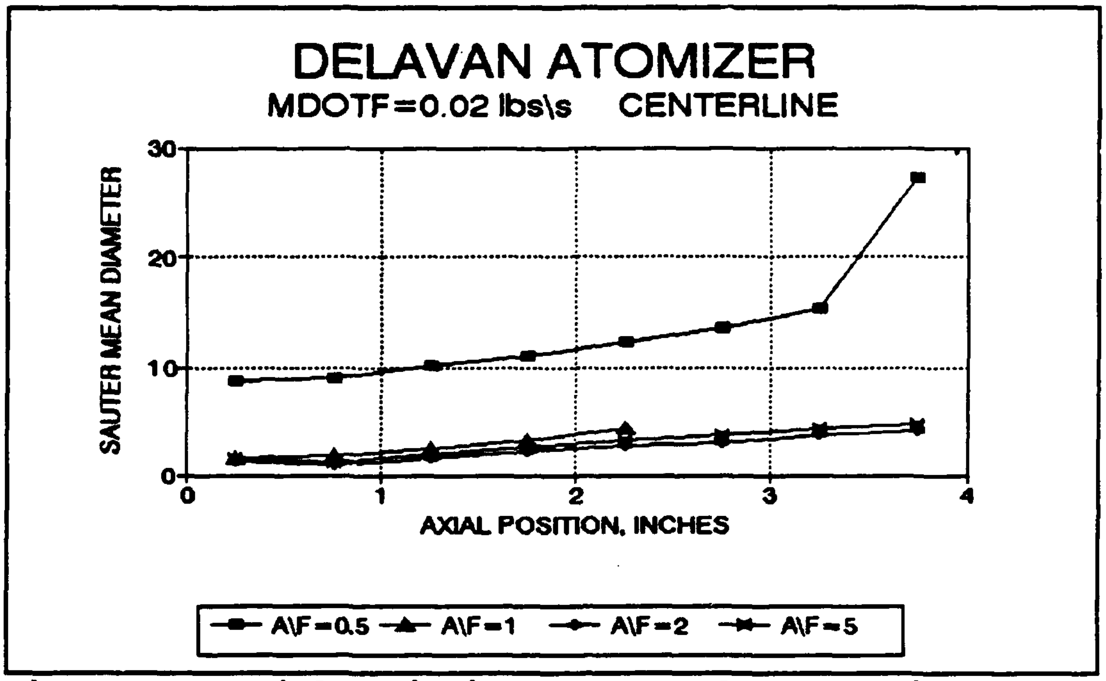

Figure 3.2: Axial Variation of D_{32}, Delavan Atomizer, 0.02 lbs/s Water, Centerline

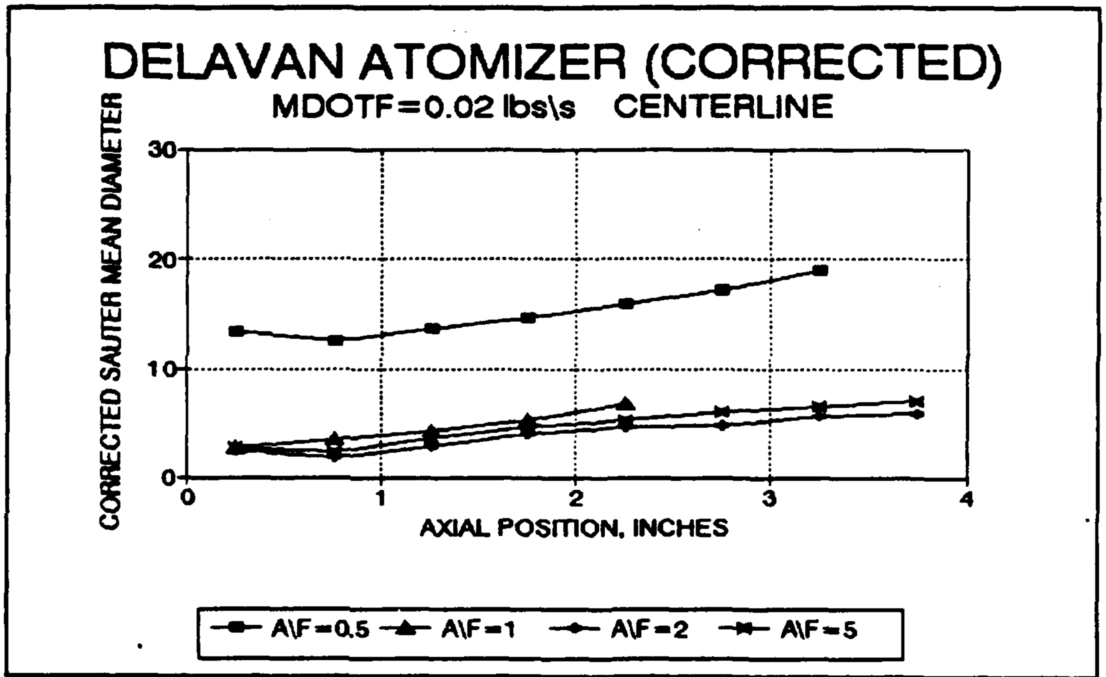

Figure 3.3: Axial Variation of D_{32}, Delavan Atomizer, 0.02 lbs/s Water, Centerline (Corrected)

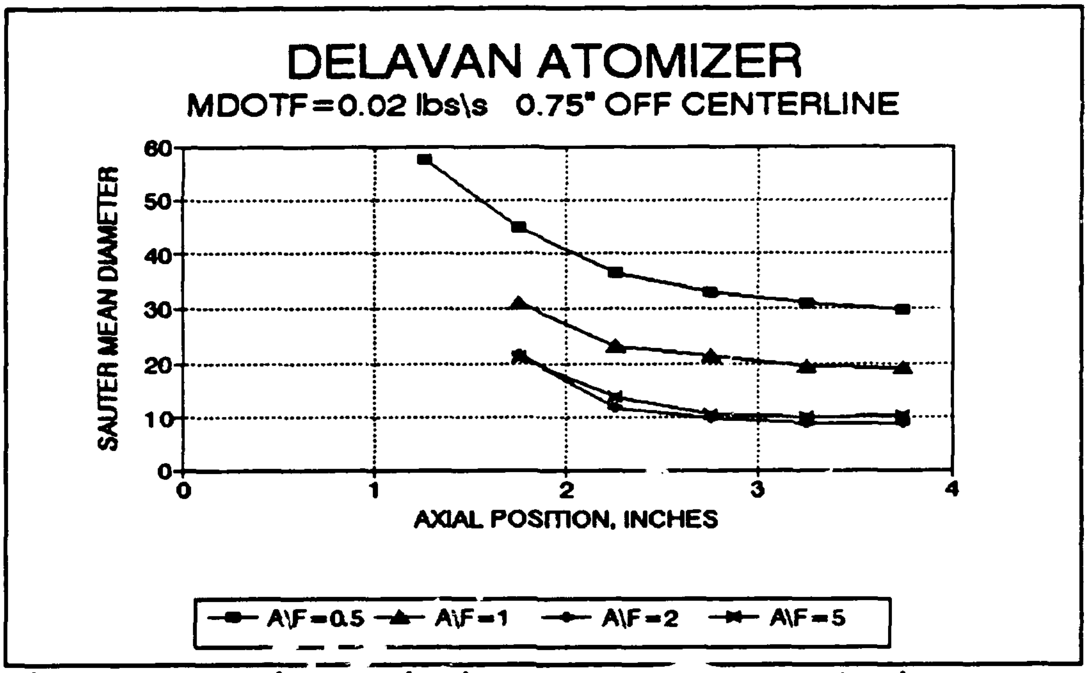

Figure 3.4: Axial Variation of D_{32}, Delavan Atomizer, 0.02 lbs/s Water, 0.75" Off Centerline

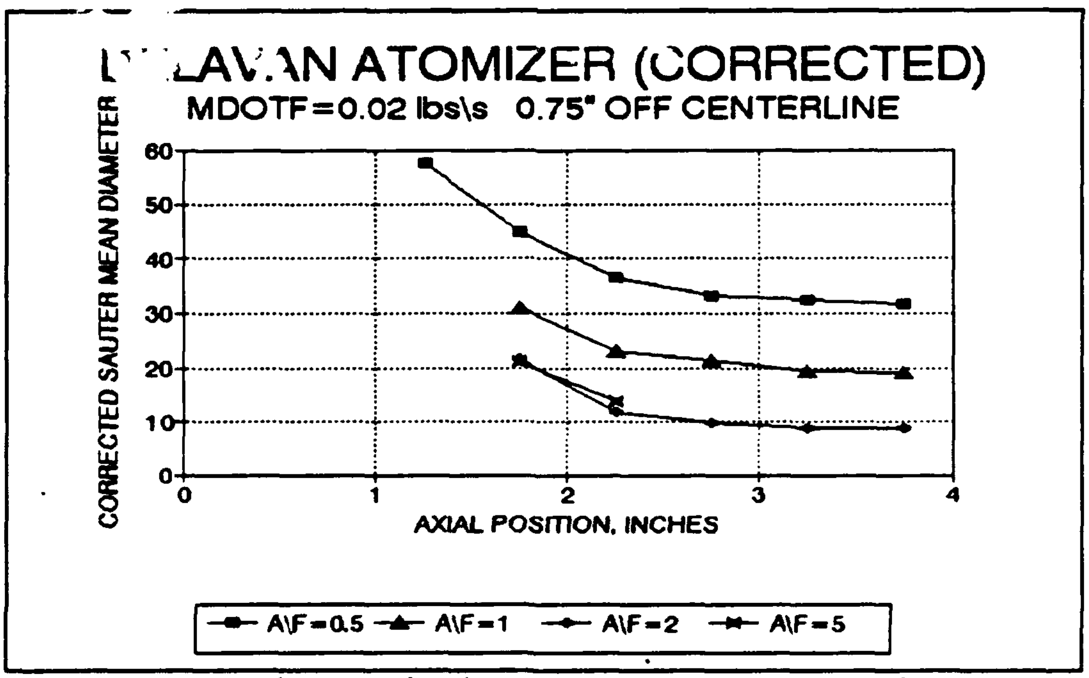

Figure 3.5: Axial Variation of D_{32}, Delavan Atomizer, 0.02 lbs/s Water, 0.75" Off Centerline (Corrected)

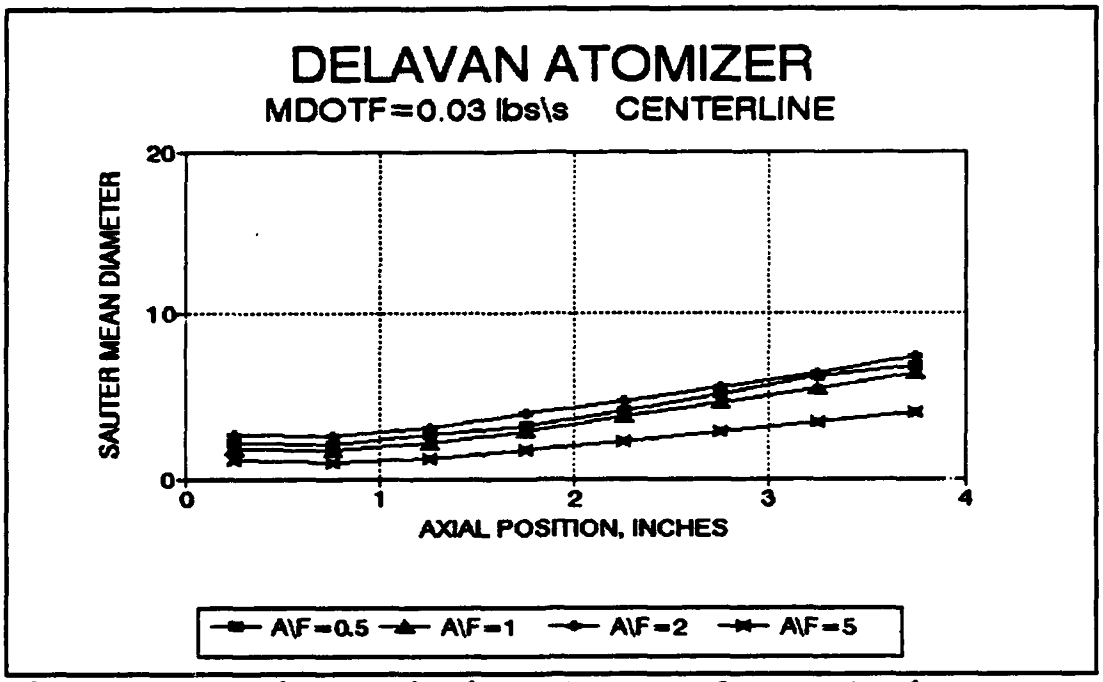

Figure 3.6: Axial Variation of D_{32}, Delavan Atomizer, 0.03 lbs/s Water, Centerline

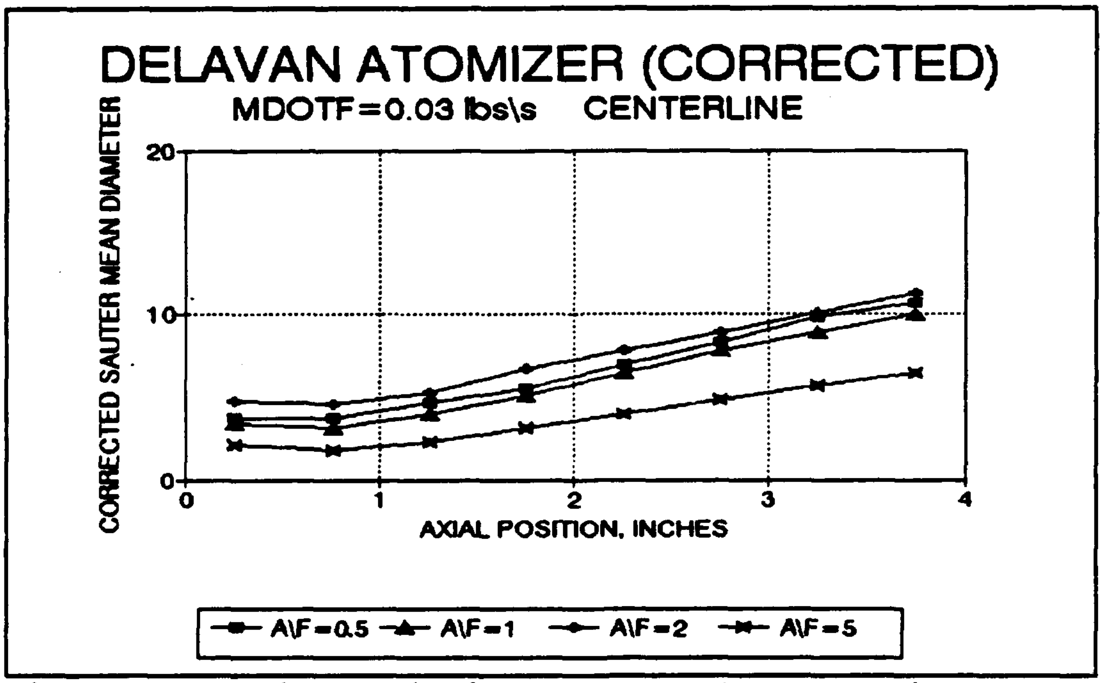

Figure 3.7: Axial Variation of D_{32}, Delavan Atomizer, 0.03 lbs/s Water, Centerline (Corrected)

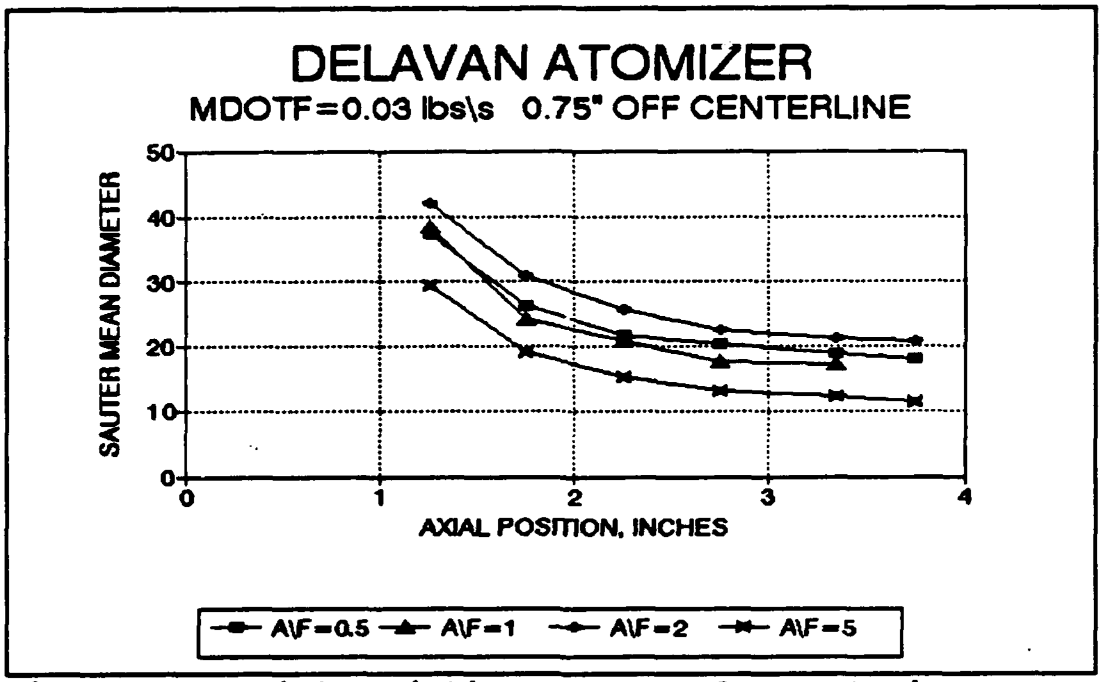

Figure 3.8: Axial Variation of D_{32}, Delavan Atomizer, 0.03 lbs/s Water, 0.75" Off Centerline

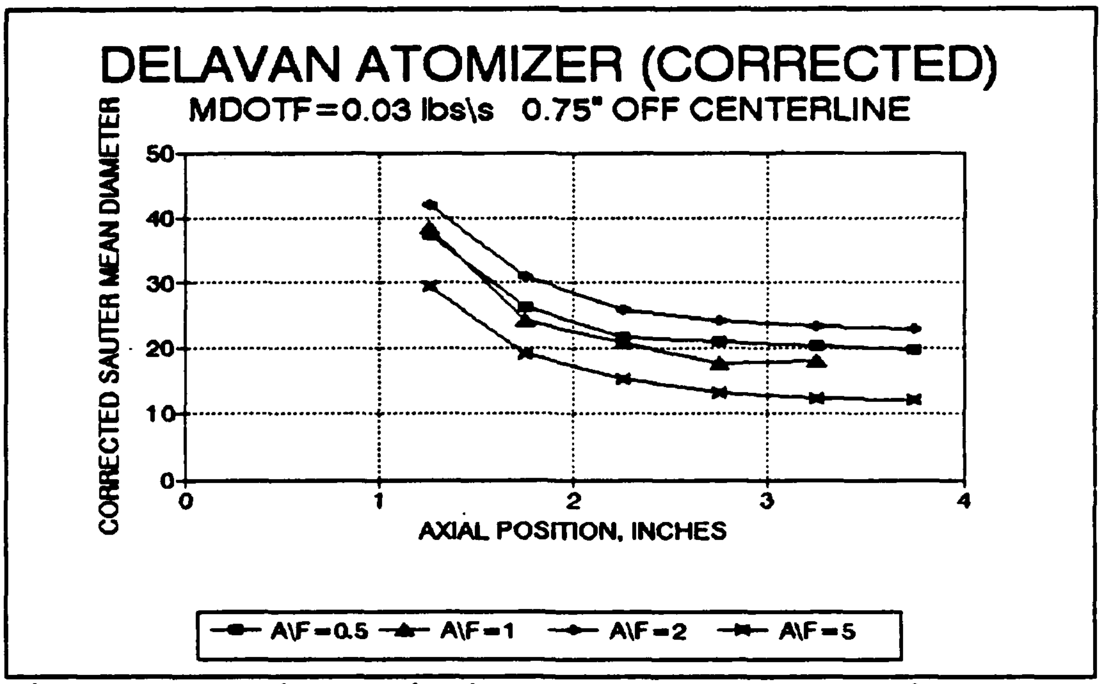

Figure 3.9: Axial Variation of D_{32}, Delavan Atomizer, 0.03 lbs/s Water, 0.75" Off Centerline (Corrected)

2. Monarch Atomizer

This atomizer was tested with water at mass flow rates of 0.02 lbs/s and 0.03 lbs/s, and air/fuel ratios of one-half, one, two, five, and ten. The raw and corrected data for each of these sets of conditions are shown in Figures 3.10 to 3.17.

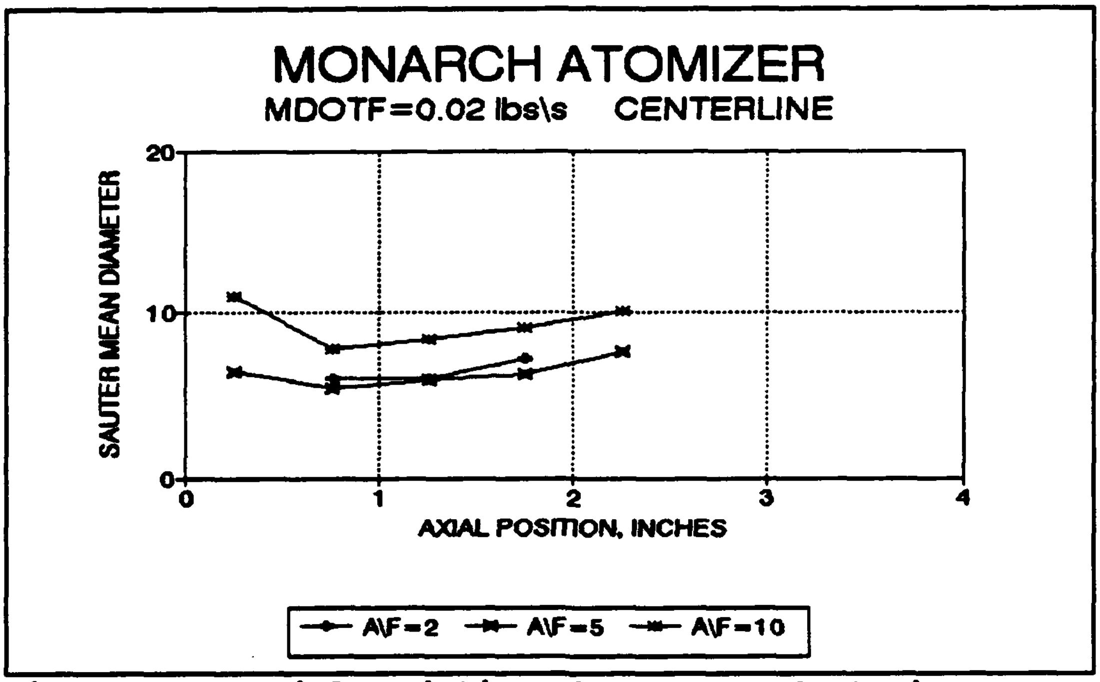

Figure 3.10: Axial Variation of D_{32}, Monarch Atomizer, 0.02 lbs/s, Centerline

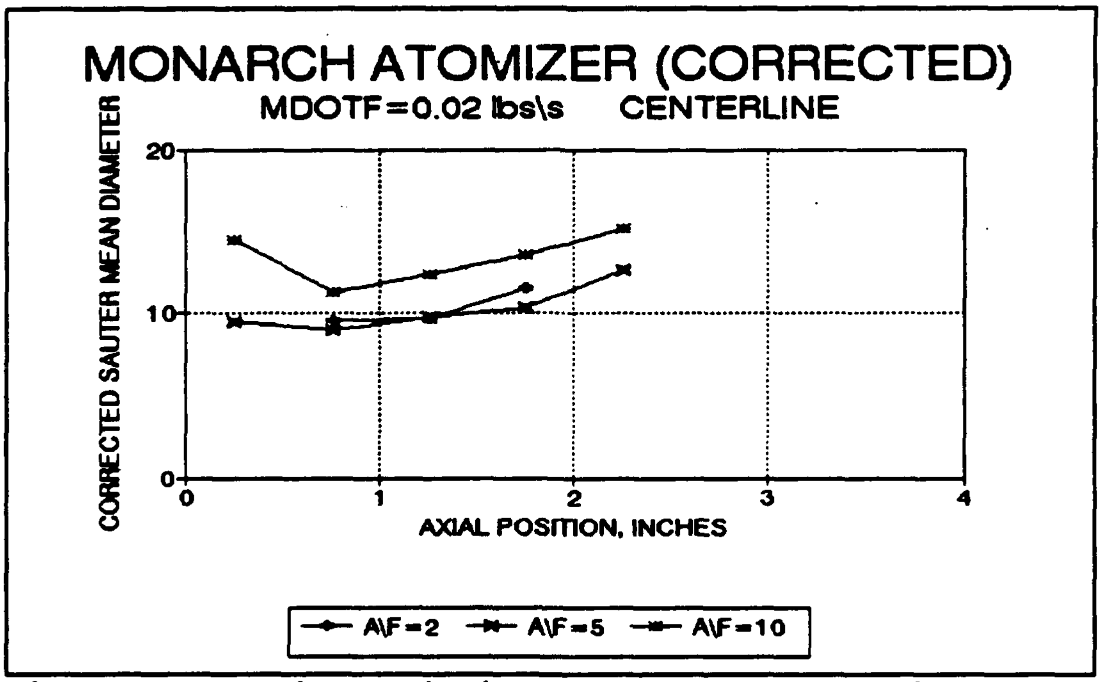

Figure 3.11: Axial Variation of D_{32}, Monarch Atomizer, 0.02 lbs/s, Centerline (Corrected)

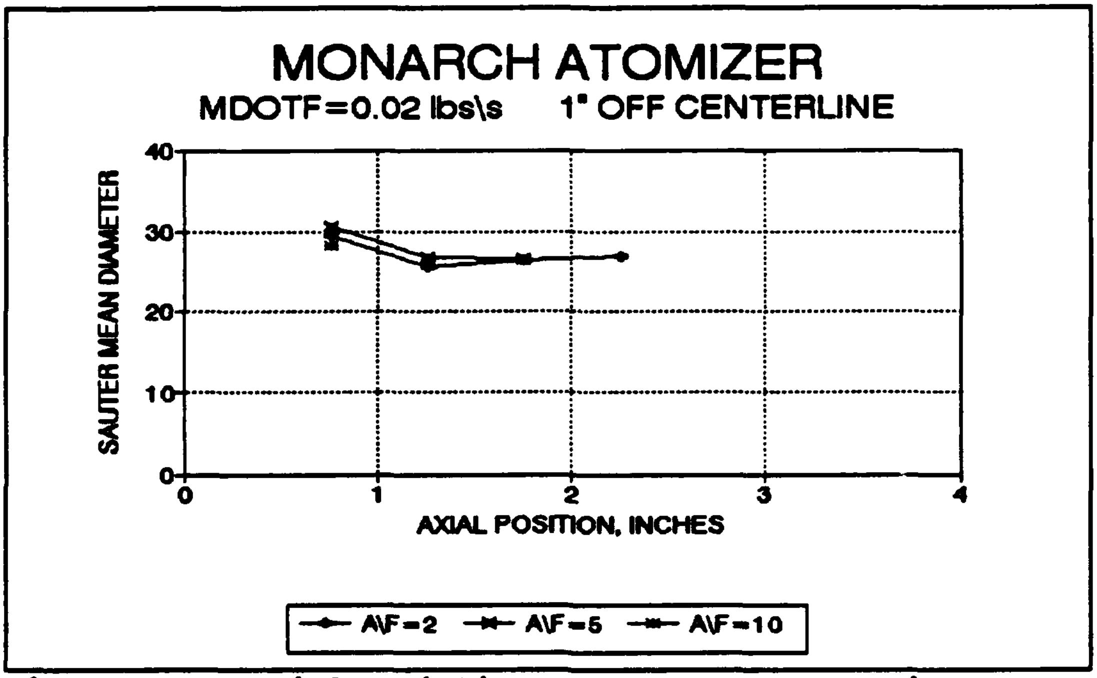

Figure 3.12: Axial Variation of D_{32}, Monarch Atomizer, 0.02 lbs/s, 1" Off Centerline

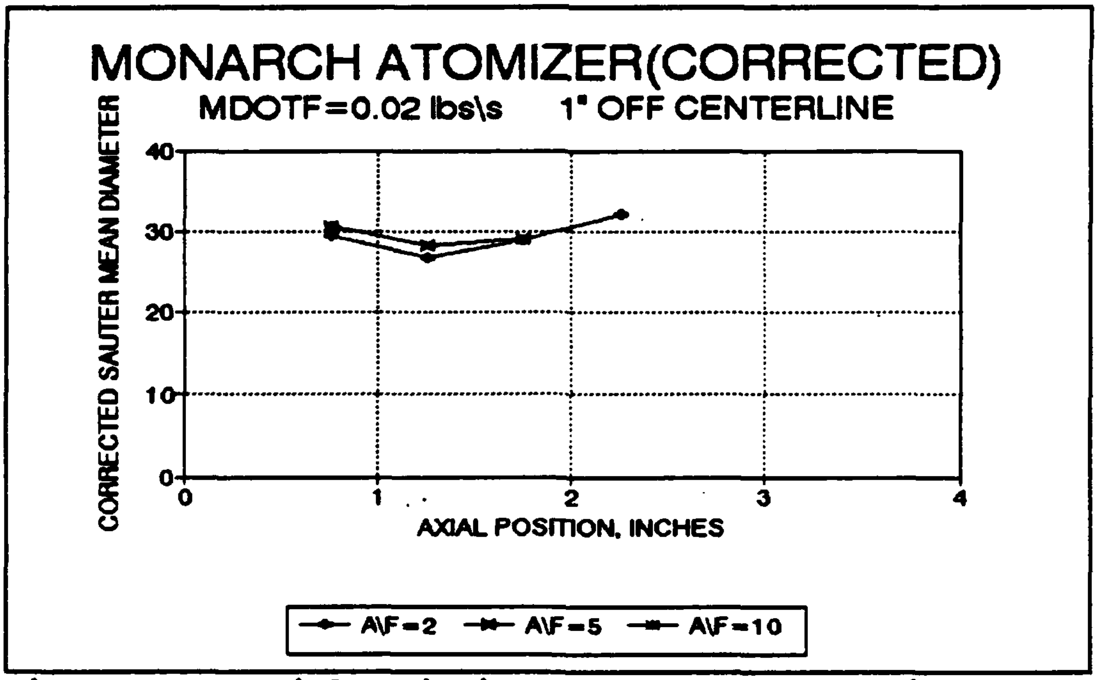

Figure 3.13: Axial Variation of D_{32}, Monarch Atomizer, 0.02 lbs/s, 1" Off Centerline (Corrected)

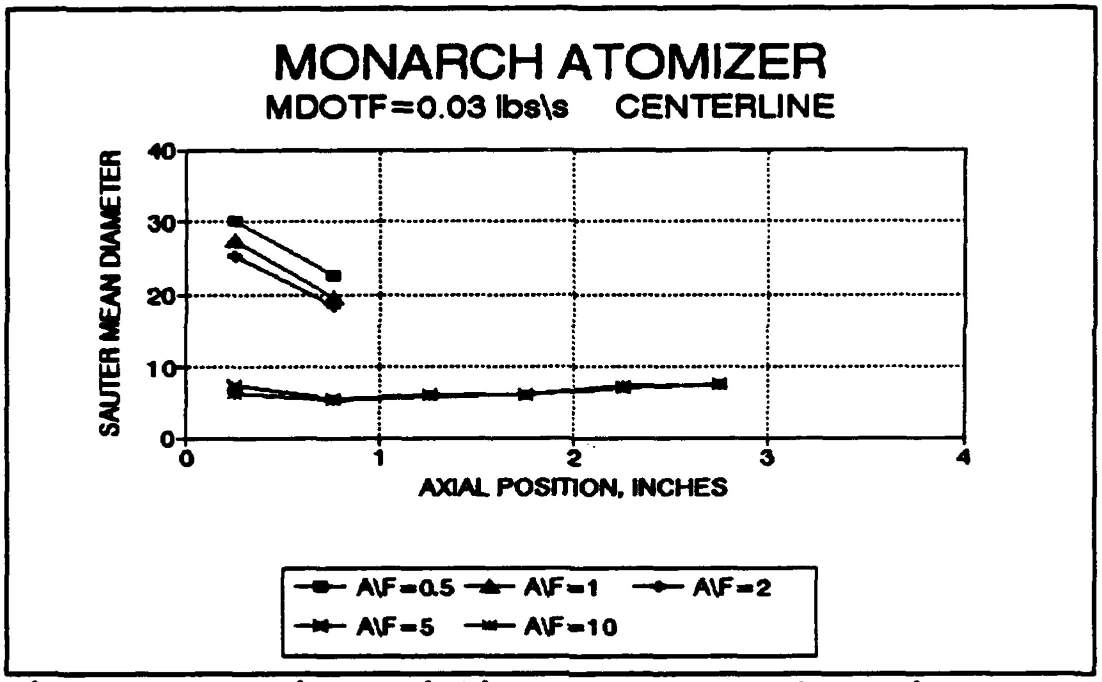

Figure 3.14: Axial Variation of D_{32}, Monarch Atomizer, 0.03 lbs/s, Centerline

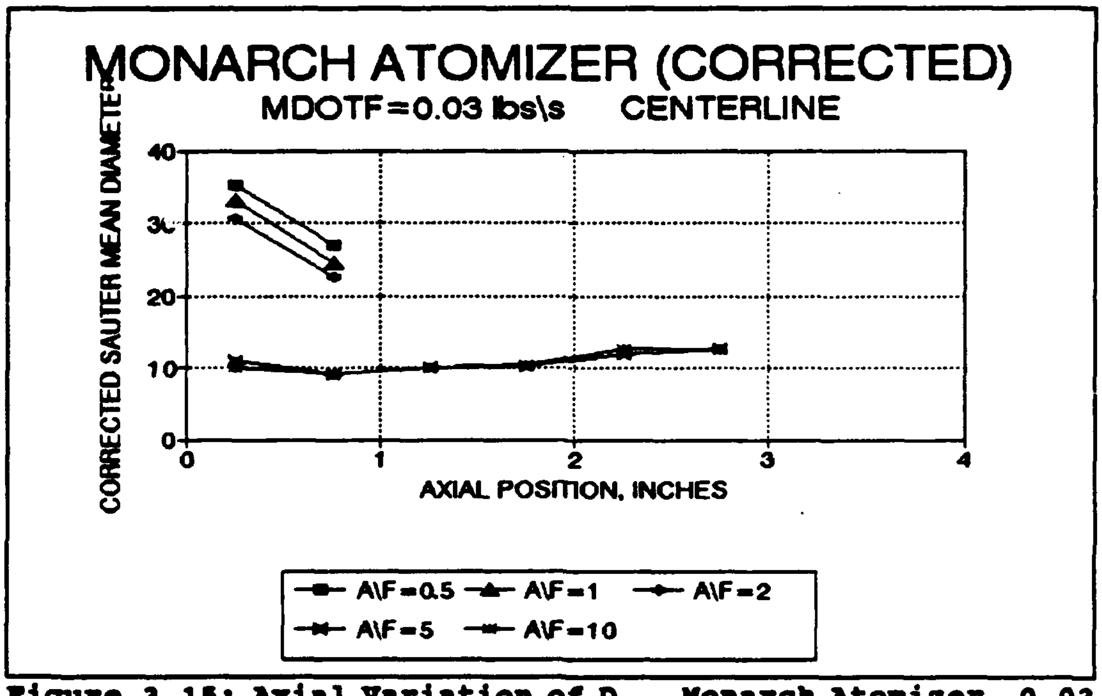

Figure 3.15: Axial Variation of D_{32}, Monarch Atomizer, 0.03 lbs/s, Centerline (Corrected)

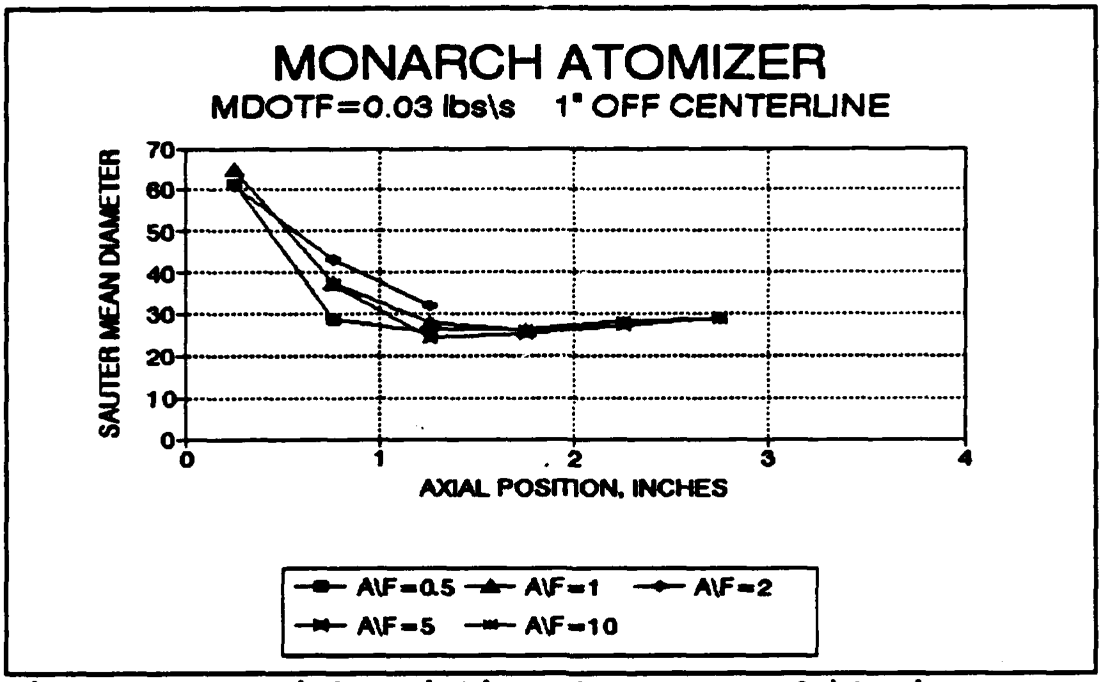

Figure 3.16: Axial Variation of D_{32}, Monarch Atomizer, 0.03 lbs/s, 1" Off Centerline

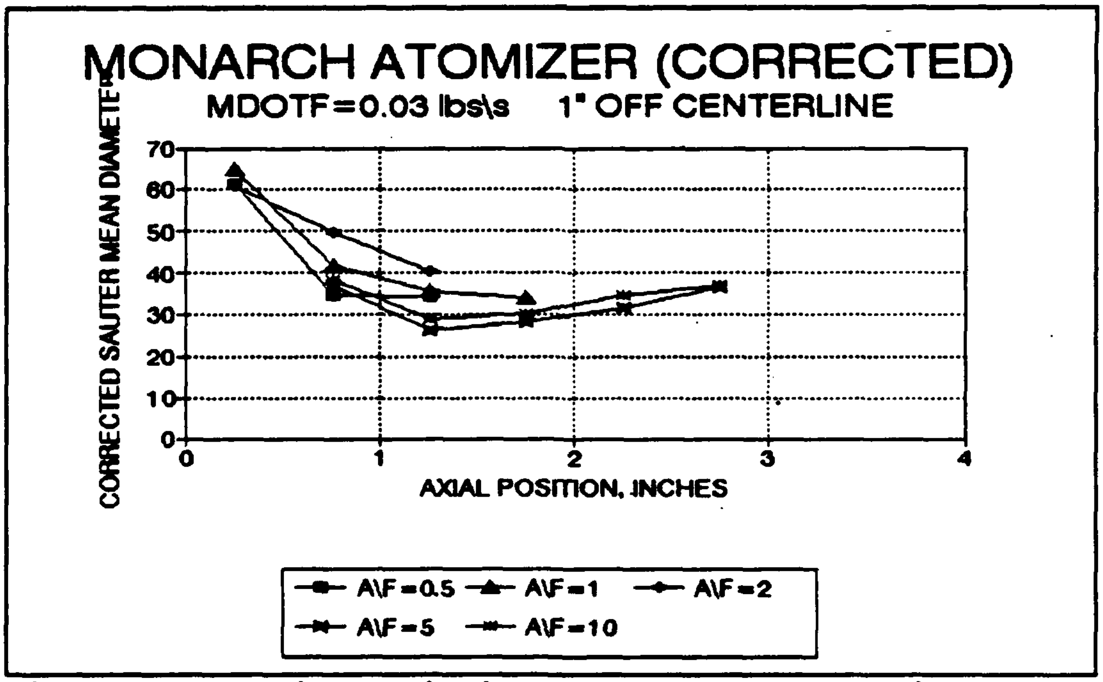

Figure 3.17: Axial Variation of D_{32}, Monarch Atomizer, 0.03 lbs/s, 1" Off Centerline (Corrected)

B. ATMOSPHERIC TESTS WITH JP-10/B_4C GELLED SLURRY FUEL

The two atomizers were next tested in open atmosphere with the JP-10/B_4C gel at a mass flow rate of 0.03 lbs/s and various air/fuel ratios. The data are shown in Figure 3.18 and 3.19. Due to the high air mass flow rates used in these tests, a significant density gradient existed near the atomizer tip, which caused unwanted steering of the laser beam. To alleviate this effect, measurements were taken at greater distances from the atomizer tip. All recorded data had values of obscuration less than 0.5, therefore application of Gülder's correction for D_{32} was not required.

The gel was contained during the atmospheric tests by injecting it from the Monarch atomizer into an eight inch diameter stainless steel pipe and by injecting it from the Delavan atomizer into a 4½" PVC pipe. Each pipe was in turn directed to a clean container in which the expelled gel was collected. Throughout the atmospheric testing the gelled slurry fuel did not flow through either pipe, but quickly re-gelled and adhered to the inside walls. At this point, it was determined that if it were injected into the windowed chamber, it would adhere to the inside walls as well as to the windows themselves, and any data obtained under these conditions would be meaningless. This characteristic of the gel, discovered during the atmospheric tests, precluded further tests with the windowed chamber in the current study.

1. Delavan Atomizer

This atomizer was tested with the JP-10/B_4C gelled slurry fuel at a mass flow rate of 0.03 lbs/s, and air/fuel ratios of four, six, eight, ten, and fourteen. The data are shown in Figure 3.18. The values of D_{32} recorded when operating at an air/fuel ratio of four were greater than 80 μm and are not presented in the Figure.

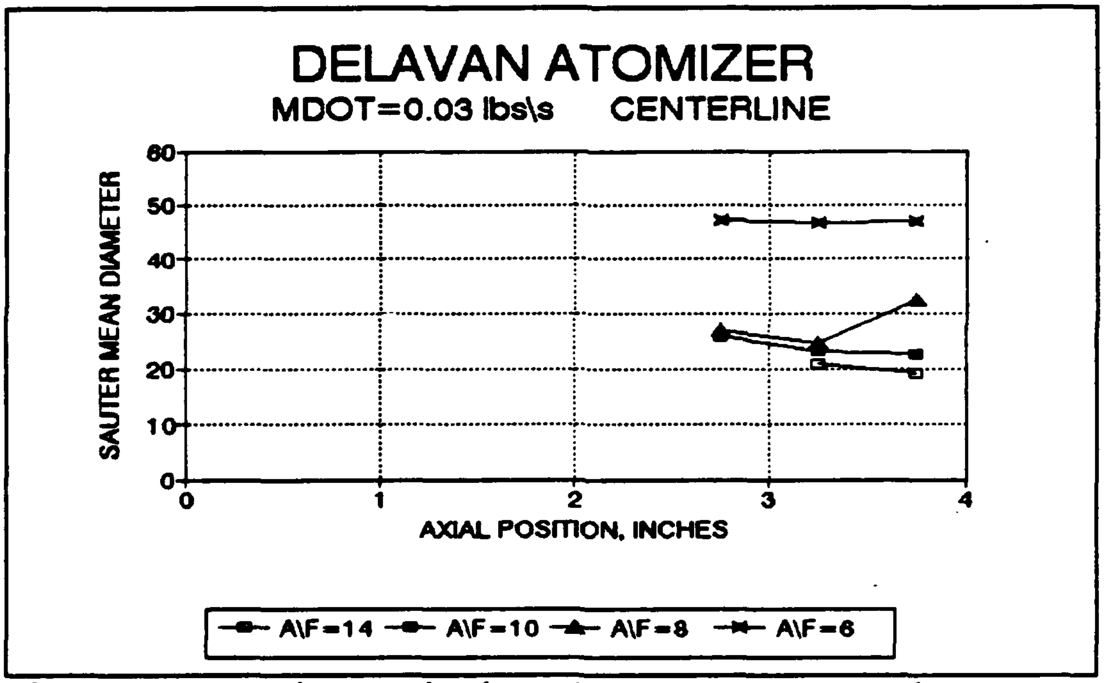

Figure 3.18: Axial Variation of D_{32}, Delavan Atomizer, 0.03 lbs/s, JP-10/B_4C Gelled Slurry Fuel, Centerline

2. Monarch Atomizer

This atomizer was tested with the JP-10/B_4C gelled slurry fuel at a mass flow rate of 0.03 lbs/s, and air/fuel ratios of four, six, eight and ten. The data are shown in Figure 3.19.

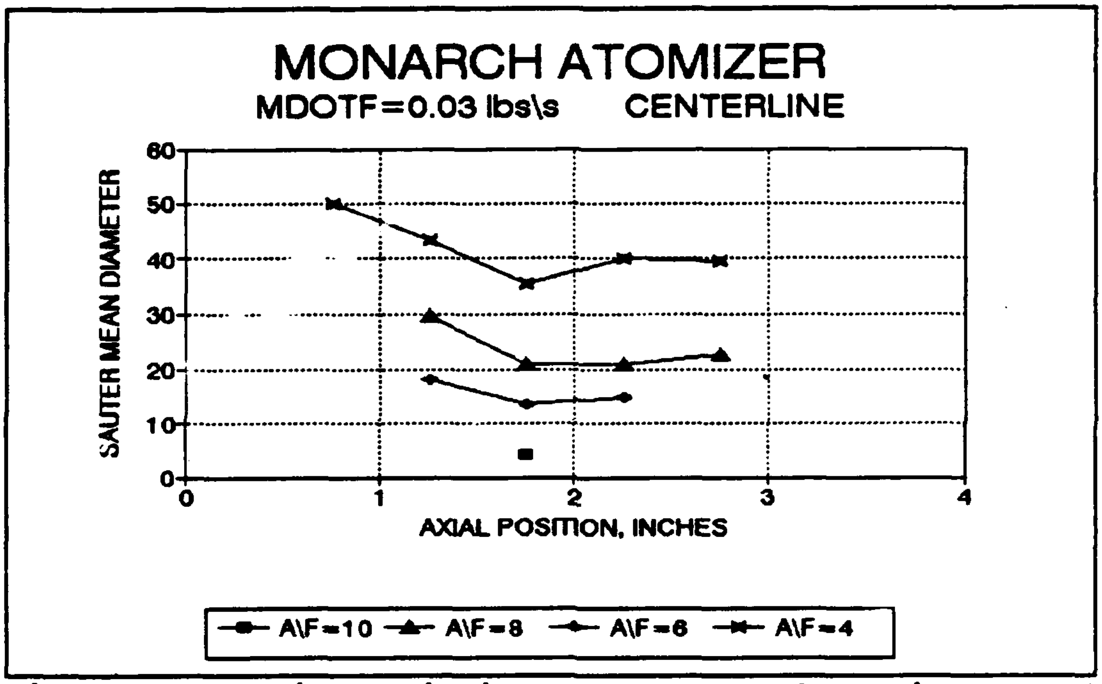

Figure 3.19: Axial Variation of D_{32}, Monarch Atomizer, 0.03 lbs/s JP-10/B_4C Gelled Slurry Fuel, Centerline

3. Tabulated Results

Table 1 is a tabulation of the values obtained for D_{32}, the location of the peaks in the volume distribution and the percent mass in the smallest measurable mass band for each atomizer. The smallest measurable particles recorded were dependent upon the focal length of the collection lens which was employed. The width of the spray pattern, which must be

kept within the vignetting distance of the collecting lens (55 mm for the 100 mm lens, 400 mm for the 300 mm lens), determined which lens was required.

Table I: D_{32}, Volume Peaks and Percent Mass in the Smallest Measurable Band for Both Atomizers

	DELAVAN			MONARCH		
A\F	(X)#	D_{32} % mass*	volume peaks+	(X)#	D_{32} % mass*	volume peaks+
14	2.25)	$21^{3.4}$	104,37,19,6			
	2.75)	$19^{4.0}$	89,37,18,6			
10	2.75)	$26^{2.0}$	120,37,6	1.75)	$4.2^{7.2}$	12,7,4,2
	3.25)	$23^{3.0}$	67,37,20,6	2.25)	$6.1^{1.7}$	12,7,2
	3.75)	$23^{3.1}$	89,37,19	2.75)	$7.3^{0.8}$	12,7,2
8	2.75)	$27^{2.6}$	140,77,37,18,6	1.25)	$18^{0.0}$	>188,30,12,7
	3.25)	$25^{3.1}$	140,67,37,18,6	1.75)	$13^{0.1}$	40,12,6
	3.75)	$32^{1.6}$	217,77,37,6	2.25)	$15^{0.0}$	30,12
6	2.75)	$47^{0.8}$	217,37,6	1.75)	$30^{0.0}$	>188,12,7
	3.25)	$47^{0.7}$	187,37,6	2.25)	$21^{0.0}$	72,30,12,7
	3.75)	$47^{0.7}$	187,37,6	2.75)	$21^{0.0}$	72,30,12,7
				3.25)	$23^{0.0}$	72,30,12,7
4	2.75)	$85^{0.2}$	>564,40,6	0.75)	$50^{0.0}$	>188,46,22,12,6
	3.25)	$91^{0.1}$	>564,40	1.25)	$44^{0.0}$	>188,27,12,6
	3.75)	$94^{0.1}$	>564,97,40	1.75)	$36^{0.0}$	72,30,14,7
				2.25)	$40^{0.0}$	72,35,14,7
				2.75)	$40^{0.0}$	72,14,7

*: Percent of mass in particles smaller than the smallest mode peak specified
+: Peaks of the volume distribution;
#: (X) indicates measurement location, inches from atomizer tip

IV. DISCUSSION OF RESULTS

As discussed above, very low atomizer air/fuel ratios (~0.05) will be required for use in ramjets. However, for high combustion efficiencies to be attained, it is currently believed that the gelled agglomerates produced must be no larger than 30-40 μm. Even this size range must be further reduced by a factor of approximately 4-5 by secondary breakup if the boron/boron carbide is to be burned efficiently. Therefore, the emphasis of the current investigation was to determine under what conditions the desired droplet sizes could be produced. If unrealistic air/fuel ratios are required, then other techniques for atomization of these highly viscous fuels must be developed. It was known that high air/fuel ratios would probably be required to obtain particles as small as 30-40 μm with gelled slurry fuels. Therefore, it was decided to test the atomizers first with water at the higher air/fuel ratios more typical of gas turbine applications.

A. RESULTS FROM ATOMIZER CHARACTERIZATION WITH WATER

1. Delavan Atomizer

The Delavan atomizer was tested at a mass flow rate significantly less than its design value. It produced a spray of very small drop sizes that increased slightly in D_{32} with

axial position along it's centerline as can be seen in Figures 3.2 and 3.3. The plotted data indicate that air/liquid ratios greater than one are needed with this atomizer to attain the minimum D_{32}. At an air/liquid ratio of one, D_{32} was approximately 8 μm, with volume peaks in the size distribution at 2 μm, 8 μm, 12 μm and 30 μm. Between 50 and 60 percent of the particle volume was contained in particles smaller than 2 μm. Thus, with this high (for ramjets) air/fuel ratio, very good combustion efficiency could probably be attained with JP-type fuels.

The D_{32} at the edge of the spray was significantly larger at axial positions closer to the atomizer tip and at the lower air/fuel ratios, as seen in Figures 3.4 and 3.5. Note that the centerline readings (Figures 3.2 and 3.3) included these drops as part of the total distribution. This behavior can be better understood by considering the shear layer that exists on both sides of a hollow cone spray pattern. The outer edge of the shear layer is established between the rapidly moving spray and the relatively quiescent atmosphere. This velocity gradient causes the large drops at the outer edge to be turned back towards the atomizer and subsequently drawn more toward the center of the spray. This shear layer also results in expansion and mixing of the spray with the atmospheric (combustion) air. The dynamics of the inner shear layer are similar, but tend to move smaller drops from the core of the spray toward the outer edge. Both of these effects result in

increased homogeneity of the spray with increased axial position.

Changes observed in D_{32} with axial position can be accounted for in several ways. Evaporation, agglomeration and drop break-up are possible, but not likely to occur due to the low temperature and pressure and to the small distances and times that these effects have to affect the spray, prior to being measured. A more likely explanation is that particles are migrating into and/or out of the measurement volume as explained above. Smaller drops move from the core of the spray toward the outer edge, and larger drops move from the outer edge into the core. This mixing by the inner and outer shear layers could account for the both the increase in D_{32} with axial position along the centerline and the decrease in D_{32} with axial position at the edge of the spray. For the latter, a more homogeneous distribution at a greater axial position of several large and many, many small drops would cause D_{32} to decrease. The total mass contained in particles smaller than 2 μm decreased from 50 percent in the near-tip region to 7 percent at a centerline axial position of 3.75 inches. Therefore, it is not the drop sizes that are necessarily changing in these regions, but the drop distributions, themselves. This effect may explain the large decrease in D_{32} with axial position for each of the off-centerline measurements taken with both atomizers.

For the higher water mass flow rate shown in Figures 3.6 to 3.9, the minimum D_{32} did not change significantly from that obtained at the lower flow rate. At this mass flow rate, the finest drop size in the edge of the spray was produced by an air/liquid ratio of 5. At an air/liquid ratio of one, D_{32} was between 2 μm and 6 μm across the entire spray, with volume peaks in the size distribution at 2 μm, 6 μm, 15 μm and 30 μm.

2. Monarch Atomizer

The Monarch atomizer was tested at nearly its design mass flow rate, and at air/liquid ratios of one-half, one, two, five and ten. D_{32} increased slightly with axial position at the lower mass flow rate, as can be seen in Figures 3.10 and 3.11. This is similar to the trend that was observed with the Delavan atomizer, however, the drops produced were approximately twice as large.

As seen in Figures 3.12 and 3.13, the larger drop sizes detected in the edge of the spray were present at all air/liquid ratios, indicating that they were more strongly a function of atomizer design than air/liquid ratio. When operating at the higher mass flow rate, as seen in Figures 3.14 to 3.17, air/liquid ratios of greater than five produced the smallest D_{32}.

The results obtained from the characterization of the two atomizers with water indicated that (1) the Delavan atomizer produced significantly smaller particles at both flow rates

investigated, (2) air/liquid ratios in excess of two were needed to obtain the best atomization under most conditions, whereas air/liquid ratios of five provided good atomization under all conditions and (3) the D_{32} obtained using the commercially available atomizers were significantly smaller than those obtained from plain-jet airblast atomizers used in Ref. 3. The lowest air/liquid ratio test with water was 0.5. The D_{32} obtained for this high (for ramjets) air/liquid ratio averaged about 10 μm for one nozzle and 30 μm for the other. These values indicated that to produce sprays with $D_{32} \approx 30\ \mu$m for the viscous gelled slurry fuel would require quite high air/fuel ratios.

B. RESULTS FROM ATOMIZER CHARACTERIZATION WITH JP-10/B_4C GELLED SLURRY FUEL

1. Delavan

This atomizer was tested at significantly less than its design flow rate and at air/fuel ratios of four, six, eight, ten, and fourteen. D_{32} generally decreased slightly (Fig. 3.18) with increased axial position (the opposite of what was observed for water) and decreased with increased air/fuel ratio, as expected. Table I shows that at all air/fuel ratios tested, practically all of the particle mass was contained in very large particles.

2. Monarch

This atomizer was tested at nearly its design flow rate and at air/fuel ratios of four, six, eight and ten. D_{32} generally decreased with increasing air/fuel ratio, but the trend was not as consistent as for the Delavan atomizer. D_{32} decreased slightly with increased axial position as it did with the Delavan atomizer under similar operating conditions.

D_{32} was approximately eight times larger with the gelled slurry fuel (Figs. 3.18 and 3.19, 40 μm) than with water (Fig 3.7, 5 μm) at a similar mass flow rate (0.03 lbs/s), air fuel ratio (5-6) and axial position (3 in.). Thus, the high viscosity of the gel resulted in much larger particles, as expected, under the same test conditions. The values obtained for D_{32} were very similar to those reported by Lipinski [Ref. 6] for the same test conditions.

At approximately the 3" position, both atomizers produced the same D_{32} (~20-25μm) at an air/fuel ratio of eight. However, at an air/fuel ratio of ten, the Monarch atomizer produced a significantly smaller D_{32} (5 μm) than did the Delavan (25 μm).

V. CONCLUSIONS

As expected, highly viscous gelled fuels produced significantly larger particles than did low viscosity liquid fuels (by a factor of about eight) when passed through airblast atomizers under similar conditions. With the use of very high air/fuel ratios (>10), very good atomization of the gelled slurry fuel can be obtained. The Monarch atomizer produced the smallest D_{32} (4 μm, A/F=10) when atomizing the slurry and the Delavan atomizer produced the smallest D_{32} when atomizing water (~1 μm, A/F=2). This indicated that nozzles which have been designed for efficient atomization of low viscosity fuels may not be optimum for high viscosity fuels.

As discussed above, the largest acceptable D_{32} for the duplex agglomerates of the gelled slurry fuel is expected to be 30-40 μm if high combustion efficiency is to be attained. Even this requires secondary breakup to the 5-10 μm size if boron based fuels are to burn efficiently in ramjet combustors with typical residence times of 4-5 msec. To obtain D_{32} values of 30-40 μm using the two airblast atomizers of this investigation required atomizer air/fuel ratios in the range of four to six. These high air/fuel ratios are unacceptable for ramjet applications where the maximum value is probably 0.10. It appears that very good secondary atomization methods and/or different types of atomizers (ultrasonic, etc.) will be

required to obtain high combustion efficiencies with these fuels if they are to be used over typical ramjet operating envelopes.

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